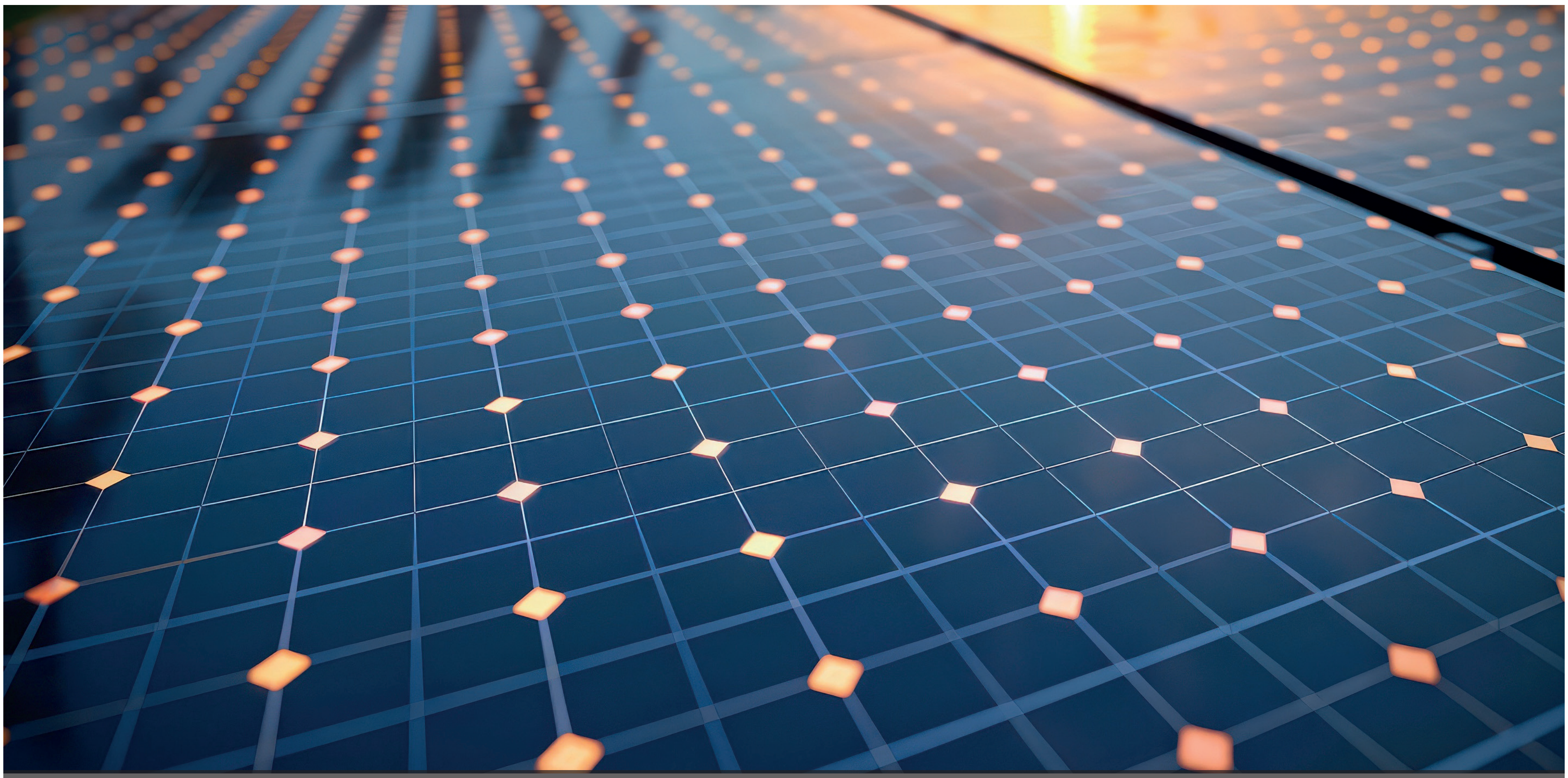

RECENT BREAKTHROUGH ADVANCES IN SOLAR CELL TECHNOLOGY

Abstract

In the past few years, solar cell technology has experienced significant breakthroughs, particularly in the development of organic photovoltaic (OPV) cells. These flexible, lightweight, and semi-transparent alternatives to traditional silicon panels are paving the way for new solar energy applications in building-integrated photovoltaics and agrivoltaics. This review highlights recent innovations in additive engineering, specifically the transition from solvent-based to solid additives, that have markedly improved the efficiency, thermal stability, and durability of OPVs. Solid additives like 2-methoxynaphthalene (2-MN) and phenothiazine derivatives have shown superior power conversion efficiencies and longer lifespans by enhancing active layer morphology and charge transport. Hybrid systems that combine non-halogenated solvent and solid additives also offer eco-friendly, cost-effective manufacturing pathways. These developments position OPVs as scalable and sustainable contributors to global clean energy goals. As the solar industry strives to meet the UN's SDG target of 90% renewable energy by 2050, the integration of high-efficiency OPVs could play a transformative role in urban energy harvesting and sustainable agriculture. This paper provides a comprehensive analysis of these advances, with a focus on performance metrics, environmental impact, and industrial scalability.

Introduction

Solar energy is one of the fastest growing and most impactful renewable energy sources, now providing approximately 9 percent of global electricity [1]. As global industries and governments work toward reducing carbon emissions and achieving sustainable development targets, innovations in solar technology have become essential. While silicon-based photovoltaic (PV) cells have historically dominated the market due to their high efficiency and long-term reliability [2], they are limited by high production costs, rigidity, and energy-intensive manufacturing processes [3]. OPV cells have recently emerged as a promising alternative. These lightweight, flexible, and semi-transparent solar cells offer unique advantages, including low-cost production, material abundance, and compatibility with surfaces where traditional panels cannot be installed [4]. However, the widespread adoption of OPVs has been held back by lower power conversion efficiencies and reduced durability under environmental stress [5]. Over the past three years, advances in additive engineering have transformed the performance of OPVs. Researchers have shifted focus from solvent-based additives to solid-state additives, which improve film morphology, thermal stability, and long-term efficiency. Some OPV devices are now reaching efficiencies near 20 percent, rivaling conventional silicon cells in performance while offering additional benefits in weight and versatility [6]. This review examines recent breakthroughs in solar cell technology, with a focus on how solid additives are advancing OPV performance. It also highlights real-world applications in building-integrated PVs and greenhouse systems, emphasizing the role of OPVs in expanding solar access and supporting global clean energy goals.

Organic Photovoltaic Cells

OPVs are an up-and-coming innovation in solar power. Unlike the widely used silicon PVs, OPVs are primarily made from polymer. The abundant material allows for capabilities to commercialize production of OPV systems [7]. They take on flexible and transparent characteristics. Their lightweight and little system structure needed can open doorways to locations the solar industry has yet to touch [7].

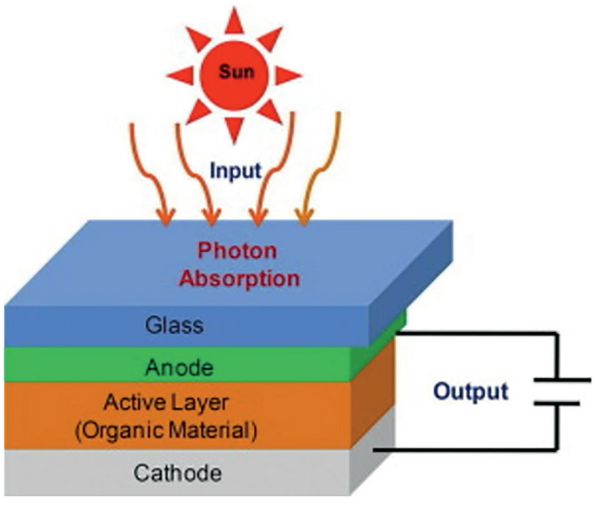

Figure 1 Layout of an OPV

Photons absorbed in OPVs generate bound excitons, not free electrons and holes, which must diffuse to heterojunctions before dissociating. This process limits carrier mobility and efficiency. In 2015, OPVs typically reached only about 7 percent power conversion efficiency [8]. However, recent breakthroughs, especially with non-fullerene acceptors, have more than doubled efficiencies, with certified devices now approaching 20 percent [9]. This brings OPV performance close to silicon photovoltaic levels, which range from about 18 to 22 percent [10].

Solvent Additives

This promising breakthrough has come from the morphology of the active layer. From their limitations in efficiency, additives can be incorporated into the production of cells. Solvent additives have been the traditional addition to the composition of OPVs. The morphology of either the acceptor or donor is altered when the solvent additive is incorporated [11]. Using solvent additives with high boiling points such as 1-chloronaphthalene (CN) and 1,8-diiodooctane (DIO) showed an optimistic increase in efficiency [12]. However, these same results did have setbacks. Studies have found that the annealing treatment of solvent additives can increase phase region size as well as crystallization in the active layer, ultimately improving [13]. However, the solvents become evaporated off in a treatment process as they're only needed in the production of films, resulting in potentially harmful solvents being released which can affect the environment as well as human health. It also causes further degradation in the cell [14], another lingering problem of OPVs. The issues that are holding OPVs back from penetrating the industrial industry may have a solution. The impact on the environment, health, as well as the cell's durability gets burdened when solvent additives are used. Although it initially seemed promising, the weighted negatives raise the need for a different solution. While still using additives, attention has been drawn elsewhere.

Solid Additives

Solid additives have become a promising addition to the solar energy industry. Like solvent additives, solids change the morphology of the high-disorder active layer. The usage of these additives appears to be considerably more efficient compared to solvents. Molecules of the solid additive 2-methoxynaphthalene

Table 1 Efficiency of OPVs with different active layers and additives

Active Layer	FF (%)	PCE (%)	Source
PM6:PY-DT	65.4 (64.5 ± 0.7)	14.47 (14.19 ± 0.18)	[15]
PM6:PY-DT (CN)	74.2 (73.4 ± 0.9)	16.61 (16.32 ± 0.19)	[15]
PM6:PY-DT (2-MN)	76.4 (75.6 ± 0.8)	17.32 (17.05 ± 0.17)	[15]
PM6:PY-DT (2-MN, o-XY)	77.3 (76.5 ± 0.8)	17.03 (16.71 ± 0.18)	[15]
PM6:Y6	71.57 (71.29 0.99)	16.11 (15.79 0.21)	[13]
PM6:Y6 (CN)	72.22 (71.25 0.74)	16.84 (16.53 0.23)	[13]
PM6:Y6 (T5)	74.47 (73.72 0.65)	17.35 (17.15 0.12)	[13]

(2-MN), have been incorporated into the active layer of a polymer solar cell. Ultimately, when tested the 2-MN had an efficiency at an astounding 17.3% compared to when tested with CN, which had an efficiency of 16.6% [15]. Solid additives can be incorporated into both donor and acceptor layers of an OPV, each contributing to different characteristics of the cell. A study by Wang et. al, used synthesized solid additives that have been incorporated into the D18 donor layer of a PSC. The results showed a higher absorption level, likely adhering to the strengthening of orderly stacking within the D18 layer. These additives can also be used in the acceptor layer, resulting in improvement in phase separation [16]. The combination of high order and increased phase separation ultimately reduces energy loss.

Due to their thin structures, OPVs are more susceptible to UV damage and weathering. While they are cheaper to produce, the replacement of these panels can become quite costly as well as wasteful. The major setback of solvent additives appears to have little interference when it comes to the use of solids additives. While solvent additives need to evaporate through the processing, solid additives can remain in the active layer [14]. This ability allows the cell to not lose durability as there is no need for residue to be dissolved off the cell through annealing treatment. They offer ways to enhance the durability of OPVs, like improving the cell's thermal capacity. Allowing a higher tolerance to higher temperatures is essential in long-lasting solar cells [17]. This has been tested with additives like 2-MN. When incorporated in, this volatile additive gradually evaporates off the panel and in doing so increases thermal stability considerably. The same trend was shown in the use of phenothiazine solid-based additives. A study by Jin-Wei Lin et. al, tested the durability of cells with and without additives. When placed under thermal strain at 80o C, the cells with additives N-Ethyl-phenothia zine (PTz-Et) or 10-Phenyl-10H-phenothiazine (PTz-Ph) both had lower degradation rates compared to those without any additives to them [18]. Synthesizing T5, a solid additive molecule, showed results that improved both the efficiency as well as the durability of PM6:Y6 binary systems. The additives greatly increased crystallinity and improved absorbance and order within the active layer. Increases were observed in all areas tested including VOC and power conversion efficiency [13]. The efficiency was even found to be higher with the use of this solid in comparison to the liquid additive CN added. The fill factor also saw significant increases. An increase in the fill factor can improve durability by facilitating better transport of electrons, ultimately alleviating stress on the device.

What is also being done is the combination of solid with solvent additives. Of course, using more environmentally friendly non-halogenated solvents, when added with solid additives, can produce a beneficial outcome. For example, in a study o-XY and 2-MN were both processed in PM6:PY-DT devices, it received a PCE of 17.03% [15]. The combination of solid and solvents provides a cost-effective alternative in comparison to cells that only contain solid additives. Having nearly the same advantages, this cheaper solution can encourage the industrialization of OPVs.

Applications for OPVs in the World

We are already starting to see the incorporation of OPV's in public spaces. OPV's flexible and translucent nature allows opportunities we have yet to see with silicon PVs. The body of system materials is significantly less compared to conventional silicon cells. Their lightweight design along with unnecessary need for support of structures and frames, allows these systems to be integrated along buildings or even windows. Michigan State University has already experimented with their applications. Ubiquitous Energy manufactured solar glass panels that were used in the Biomedical and Physical Sciences building on campus. These panels provide enough energy to light up the building's atrium. NEXT Energy Technologies has also recently dived into OPV windows. If added onto buildings, they can offset 20-25% of their energy load [19]. An additional perk to these panels is that they capture and convert more infrared light, allowing places in warmer climates to have less of a toll on cooling systems. For now, they are in company buildings but are currently in the process of shifting to higher production and commercialization. More opportunities for these windows can start to be seen in the upcoming years.

The application of OPV systems is starting to gain traction in a different sector: agriculture. Their semi-transparent qualities can be incorporated into greenhouses. Modeling as well as experiments have been done to see if this could be a feasible opportunity. PVs have been previously experimented with in greenhouses but lacked even lighting for plants to thrive in. The bulky and opaqueness of silicon PVs only resulted in patchy lighting and an expensive addition. The translucency of OPVs can allow more photons to reach plants while also absorbing and converting into energy themselves [20]. The lower costs to produce OPVs also seem to level out the lower efficiency of these systems. In Arizona, Rebekah Waller et. al, experimented with the influence of OPV shading on the growth of tomato plants. In climates such as Arizona's, proper shading can protect plants from the strong solar radiation, especially in greenhouses where they get near full sun. The OPVs still allow sun to be transmitted but capture some of the photons for their own use. When tested with tomato plants, there was little difference in growth compared to ones with a shade cloth [21]. This could be a likely opportunity for agrivoltaics to expand, allowing greenhouses to function normally while also contributing to a supply of energy.

The Solar Industry still has a way to go to meet the SDG of 90% renewable energy by 2050 [22]. But these recent advancements have set a pathway for the upcoming years, giving optimism to reach that goal. The newfound qualities of solid additives in OPVs encouraged the advancement we have been seeing. Solar energy's incredible capabilities are still being researched and improved upon. With the progress that has been made these past few years, the continuation of this trend can be promising [22].

Conclusion

The past three years have marked a turning point in solar cell innovation, particularly in the development and optimization of OPV technology. As the global demand for clean and adaptable energy solutions grows, OPVs have emerged as a flexible and sustainable alternative to traditional silicon-based panels. Their low material cost, mechanical flexibility, and potential for integration into non-traditional surfaces make them ideal for a wide range of applications, from smart building windows to energy-generating greenhouses.

The shift from solvent-based to solid-state additives has significantly improved the performance, stability, and environmental safety of OPV cells. Solid additives such as 2-methoxynaphthalene and phenothiazine-based compounds have enhanced the active layer morphology, increased power conversion efficiency, and reduced degradation under thermal stress. These improvements have brought OPVs closer to commercial viability, with some devices reaching efficiencies above 17 percent. Combined approaches that use both solid and environmentally friendly solvent additives offer additional pathways to scalable and cost-effective OPV manufacturing.

As researchers continue to refine additive strategies and explore new material systems, OPVs are poised to become a key player in the renewable energy sector. Their ability to complement existing solar infrastructure while expanding into previously inaccessible markets supports the broader goal of achieving a sustainable and decentralized energy future. With continued innovation, OPVs can help accelerate the global transition to renewable energy and contribute meaningfully to long-term climate goals.

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